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DRY AEOLIAN DUST ACCUMULATION IN ROCKY DESERTS: A MEDIUM-TERM FIELD EXPERIMENT BASED ON SHORT-TERM WIND TUNNEL SIMULATIONS

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ABSTRACT

The spatial pattern of medium-term (a few months) dry aeolian dust accumulation in rocky deserts is predicted using short-term deposition and erosion experiments in a wind tunnel. The predictions are tested in a field experiment set up in the northern Negev Desert of Israel. The results show that superimposing wind tunnel deposition and erosion maps usually leads to correct predictions of medium-term dust accumulation. The predictions are somewhat less confident near the inflection lines of windward hillslopes, where small-scale irregularities in the local topography make it difficult to locate the exact position of the areas of little accumulation. Elsewhere in the topography predictions are good, and the method works satisfactorily.

Highest accumulation occurs on concave windward slopes and, to a lesser extent, on slopes parallel to the wind. Little accumulation occurs on the convex windward slopes and in dust separation bubbles. The smallest accumulation rates are observed immediately upwind of the top of pronounced hills and on leeslopes.

The rate of dry dust accumulation measured during the field experiment varied from 17 to 93 g m^{-2} a^{-1}, depending on the topographic position of the accumulation plots. For most plots, it was of the order of 30–60 g m^{-2} a^{-1}.

KEY WORDS: dust; dust accumulation; desert; wind; wind tunnel; Negev

INTRODUCTION

Many arid areas on Earth are characterized by the presence of fine, natural dust particles in the atmosphere. These particles play an important role in the dynamics of the lower atmosphere (Offer and Zangvil, 1992) and on the Earth's surface itself (Goudie, 1978; Goossens and Offer, 1997). They also strongly affect, directly or indirectly, the biological activity in these regions (Jones and Shachak, 1990). Settling dust provides organisms with different kinds of nutrients (Esser, 1989; Offer *et al.*, 1992; Littmann, 1997), and when it accumulates, it significantly contributes to soil development (Yaalon and Ganor, 1973, 1975; Gile *et al.*, 1981; Gerson *et al.*, 1985; Gerson and Amit, 1987; McFadden *et al.*, 1987; Reheis, 1990; Reheis *et al.*, 1995). The dust also plays a fundamental role in the storage of water in a rocky desert, since its storage capacity is much larger than that of most desert lithosols. As such, aeolian dust is one of the most important components in the desert ecosystem (Jones and Shachak, 1990).

Quantitative studies of dust accumulation in deserts are scanty. Although most studies on dust accumulation correctly point to the significance of accumulation for soil formation, they remain merely descriptive in their approach or provide only crude estimates of the accumulation rates. Many data published were obtained using specially designed deposition traps (see examples in Goossens and Offer, 1990; Pye, 1992; Reheis and Kihl, 1995; Littmann, 1997; Reheis, 1997). These can reveal the spatial or temporal

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variations in the dust deposition (and/or accumulation) patterns, but do not sufficiently simulate the natural structure of a rocky desert surface. The extrapolation of data, obtained with such traps, for the long-term evolution of the desert surface remains doubtful.

The significance of a rocky desert surface as a natural dust trap has been recognized and investigated by many researchers (Greeley and Iversen, 1981; Ford *et al.*, 1982; Wells *et al.*, 1982, 1985; Gerson *et al.*, 1985; Gerson and Amit, 1987; Goossens, 1995). However, none of these studies focuses on the spatial variation of dust accumulation. Studies dealing with spatial patterns in loess deposits (the result of long-term dust accumulation) clearly show that the rate of accumulation is strongly correlated with the local topography (Peeters, 1986; Goossens, 1988a, 1997), and that this correlation is not only caused by syngenetic or post-genetic redistribution by water, but also, and even predominantly, by the wind. Therefore, it is important to know how topography affects the aeolian accumulation pattern of dust.

Aeolian accumulation is the combined result of aeolian deposition and aeolian erosion. The effect of topography on aeolian dust deposition has been investigated in detail in wind tunnels (Goossens, 1988a, 1988b, 1989, 1996a, 1997; Goossens and Offer, 1990; Offer and Goossens, 1995) and in field experiments (Goossens, 1988c; Goossens and Offer, 1990, 1993; Offer and Goossens, 1995). The effect of topography on aeolian dust erosion has also been investigated (Offer and Goossens, 1994; Goossens and Offer, 1997). These studies show that short-term wind tunnel simulations can accurately predict the deposition and erosion patterns created during short-term events (lasting from a few hours to a few days, such as single storms, either with or without dust). The question arises whether short-term wind tunnel simulations can also provide useful information with respect to the medium-term (or even long-term) accumulation of dust, i.e. the accumulation in a period of at least a few months or even longer. Such medium- and long-term predictions are of great importance, not only for geological, geomorphological or pedological issues, but also for ecological, biological and many more applications, as indicated earlier.

In this study, we explore the possibilities of using short-term wind tunnel simulations for the prediction of medium-term dust accumulation. The patterns of aeolian dust deposition and aeolian dust erosion created on a topographic scale model of a hilly desert region are first investigated separately and then combined into a new pattern of expected accumulation. The expected pattern is then tested in a medium-term experiment carried out during the dry season. In the present stage, we restrict ourselves exclusively to dry aeolian accumulation. The effects of water flow on the redistribution of accumulated sediments will be investigated later.

THE EXPERIMENTAL FIELD

The area selected for the wind tunnel and field measurements is situated in the northern part of the Negev Desert of Israel, close to the ancient Nabatean settlement of Avdat (Figure 1). It is more or less ellipsoidal in shape, and has an area of about 53 ha. A detailed description of the climatological and geomorphological characteristics of the test field is provided by Goossens and Offer (1990); the major aspects are summarized below.

In Avdat, the climate is affected by the subtropical high-pressure belt mainly during the summer and by mid-latitude low-pressure systems during the winter. The predominant winds blow from the north, northwest and west. Annual average temperature is around 18°C, with large differences between winter and summer and between day and night. Summers are hot and dry, with the dominance of the daily sea breeze circulation. Winters are wet and cool, with considerable cyclonic activity (Offer and Zangvil, 1992). During the summer, no intense cyclones affect the region, and thus no intense dust storms are observed. Extreme situations of dust storms (with airborne dust concentrations of several thousand micrograms per cubic metre) are associated with migrating synoptic systems and with wind directions from the westerly (sometimes also from the easterly) quadrant.

The landscape near Avdat consists of stony hammadas, which are developed on different elevation levels. They include both large and small plateaus and wide wadi depressions. Many of the plateaus are dissected at their borders by valleys, the depth of incision of which may reach more than 50 m but is usually restricted to 10–30 m. Figure 2 shows a relief map of the experimental field. The position of the test area itself is indicated by a thick black line. The test area is situated on an interfluve between a large, wide wadi depression (in the

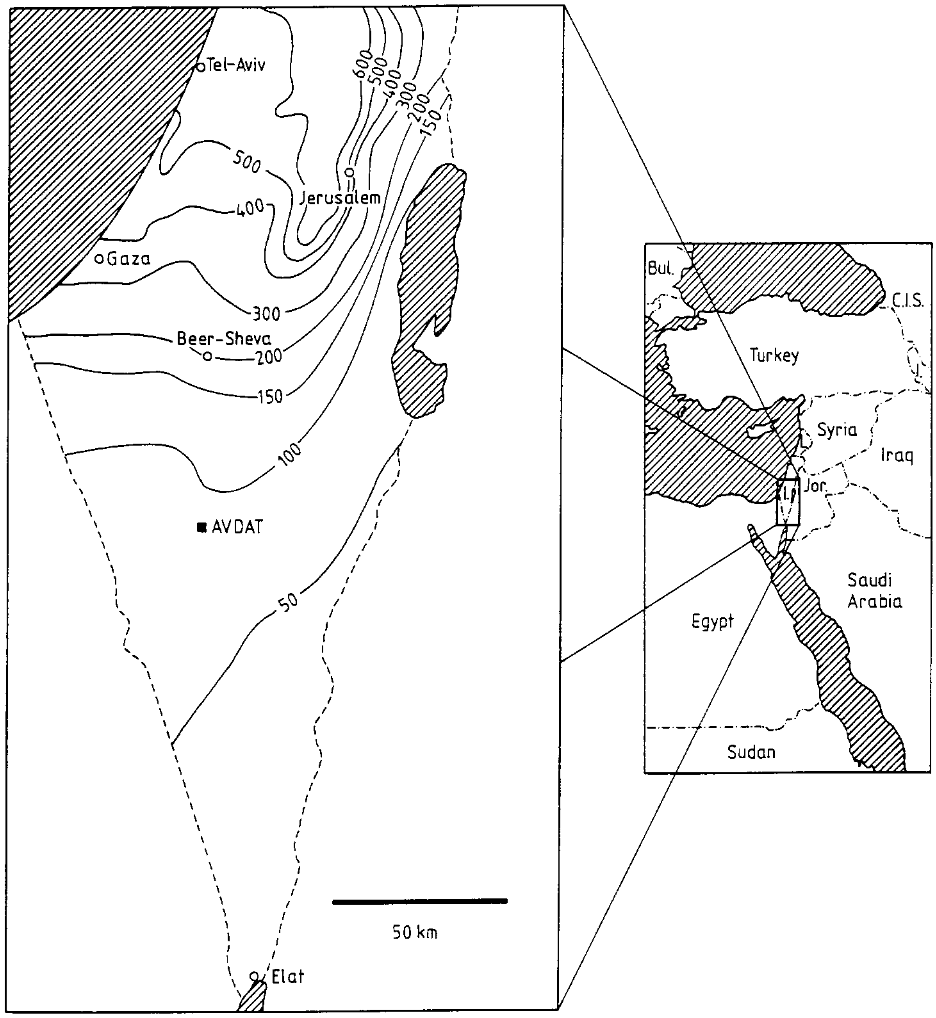

Figure 1. Situation of the Avdat experimental field

west) and one of its eastern tributaries (in the north and the east). It is surrounded in the NE, E and SE by a plateau, situated at an elevation of about 620 m. Part of this plateau penetrates into the southeastern section of the test field, where it forms a hill with an elevation of 608 m. A second hill (603 m) appears north of the plateau spur. It is separated from the latter by a deeply (>25 m) incised valley. In the western part of the test field, a second plateau occurs at an altitude of about 560 m. The western part of this plateau is formed by a relatively steep slope. A valley system, composed of three branches, penetrates from the eastern wadi into the 560 m plateau. Colluvial deposits, consisting of very fine and well sorted limestone pebbles, are found near the confluence area of the valleys. Northwest of the confluence, an ellipsoidal hill, 560 m in elevation, has been cut off from the 560 m plateau.

The subsoil in the test field is composed of limestone and chalk, with variable amounts of chert. It is partly covered by a thin layer (some centimetres to some decimetres) of loessic material mixed with limestone and chert pebbles up to 20 cm in diameter. No continuous loess cover is found, but loess crusts of 2–4 mm in thickness are observed at many locations. They consist of some 25 per cent fine sand, 55 per cent silt and 20 per cent clay (Bruins, 1986).

Vegetation is scanty. It is completely absent on both of the hills in the east of the experimental fields, and occurs only very sparsely on the 560 m plateau and the northernmost hill. It is only on the valley floors that

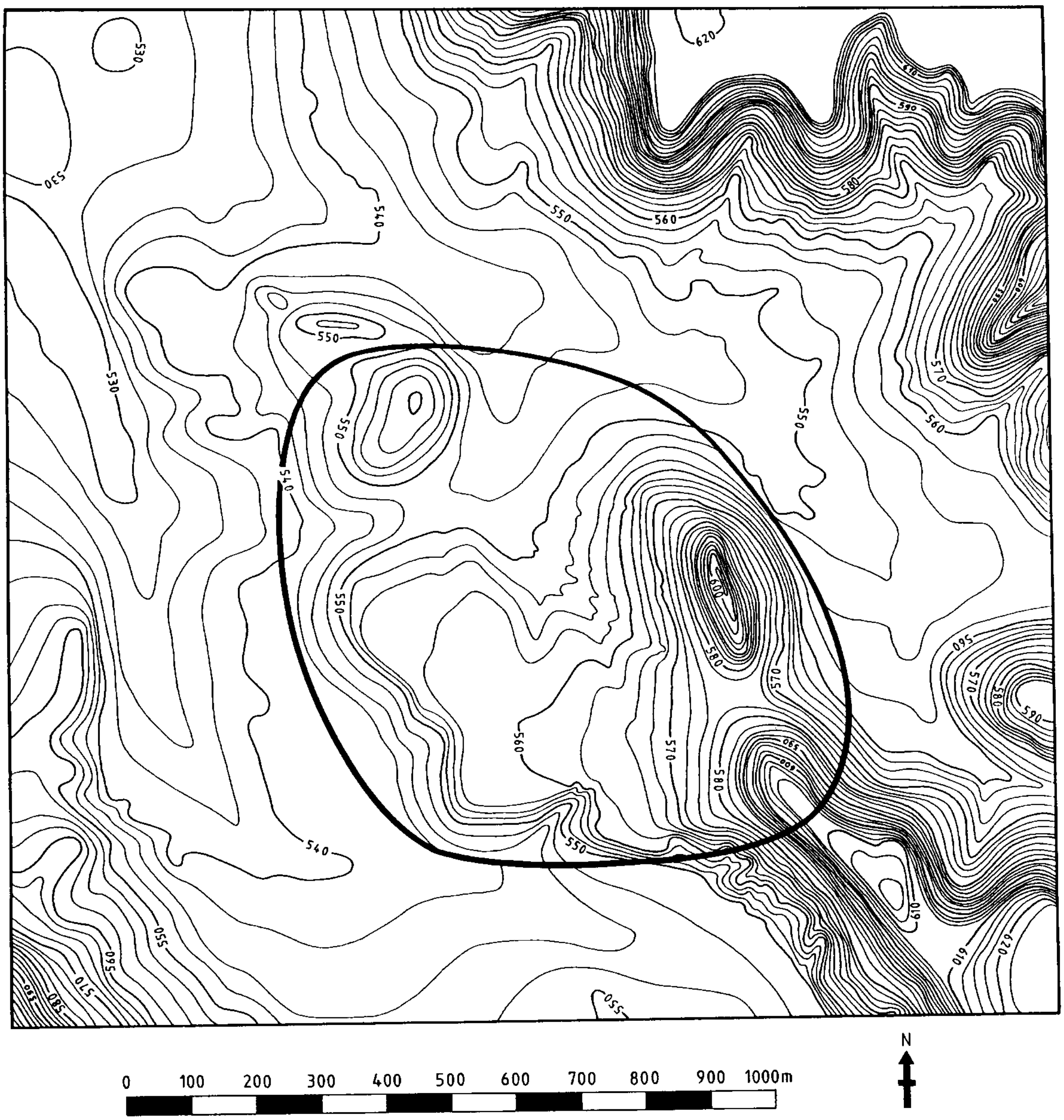

Figure 2. Relief map of Avdat. The thick black line indicates the test field

vegetation cover becomes denser. Nearly all vegetation is composed of small (0·2–0·3 m), discontinuously dispersed shrubs, which occur predominantly in small single bushes instead of in a continuous cover. Typical representatives are *Artemisia herba-alba* and *Zygophylletum dumosi*.

WIND TUNNEL FACILITIES AND SCALE MODEL

All wind tunnel experiments were carried out in the closed-return wind tunnel of the Laboratory for Experimental Geomorphology (Katholieke Universiteit Leuven, Belgium). The tunnel contains two test

sections. All experiments were carried out in the large test section, which is 7·6 m long, 1·2 m wide and 0·6 m high. During the deposition experiments, dust was added to the air current by connecting an Engelhardt laboratory dust cloud producer to the tunnel. This apparatus ensures a continuous feed of dust particles to the airflow, and allows the operator to adjust dust discharge. Further technical details of the wind tunnel and the dust cloud producer can be found in a description by Goossens and Offer (1988).

The scale model used is described in detail in Goossens and Offer (1990). It was constructed from polystyrene plates 1·86 mm thick, which were cut along contour lines copied from the topographical map of the study area. Gluing together the plates produced a rough, terraced scale model containing both the experimental field and its surroundings. The area corresponding to the proper test field was later smoothened with gypsum and then roughened again by adding a homogeneous cover of fine sand grains (diameter 125–175 μm) to the model surface. This was done to establish roughness similitude between prototype and model. Blockage of the scale model was nearly 10 per cent. Horizontal scale was 1:2500 and vertical scale 1:1342, resulting in a height distortion of 1·86 times. Vertical distortion was necessary to retain some small topographic incisions in the central part of the area. Tests by Goossens and Offer (1990, 1993, 1997) and Offer and Goossens (1994) showed that a small vertical distortion will not lead to serious problems in the type of simulations described in this paper.

METHODOLOGY AND PROCEDURE

Deposition and erosion patterns obtained in the wind tunnel

In a previous study (Goossens and Offer, 1988), simulations of aeolian dust deposition and erosion on the Avdat scale model were carried out for different wind directions varying between north and southwest. In each simulation, 6 m upwind fetch in the wind tunnel was covered with a plastic sheet with gentle undulations. The boundary layer created was 22·8 cm thick (corresponding to 306 m in the field) and had a velocity profile with a power exponent of 0·16 and a z_0 value of 143 μm. It was a very good replica of the natural boundary layer in Avdat (more details may be found in Goossens and Offer, 1990; Offer and Goossens, 1994).

In the deposition experiments, air-dry Belgian Brabantian loess sieved at a diameter of 63 μm was introduced to the air in the return section of the tunnel. The median diameter of the loess was 25 μm, which closely corresponds to the size of the dust that settles near Avdat during dusty events (Yaalon and Ganor, 1979). Dust discharge produced by the dust cloud machine was 7 kg h^{-1}, total time duration of each experiment 6 min, and free stream wind velocity in the tunnel, 152 cm s^{-1}. After each experiment, the sedimentation pattern of the dust on the scale model was carefully mapped on a base map showing the contour lines of the test area. Four sedimentation classes were retained: ‘very little sedimentation’, ‘little to moderate sedimentation’, ‘much sedimentation’ and ‘very much sedimentation’.

In the erosion experiments, the scale model was covered by a thin layer of Brabantian loess before each experiment. To ensure a loess cover of equal thickness over the entire scale model, the loess was spread homogeneously over the surface by means of a small 125 μm sieve. In each simulation, wind speed in the tunnel was progressively increased until the first erosion features on the model appeared. The experiment was then stopped, and the eroded areas were marked on the model. The wind tunnel was then restarted, and this procedure was repeated a total of three times. Following completion of the experiment, the scale model was photographed vertically. The slide was projected on the topographical map of Avdat, and the erosion areas were carefully transferred to the map. Three erosion classes were retained: ‘weak erosion’, ‘moderate erosion’ and ‘strong erosion’.

The accuracy of the wind tunnel maps was tested during several natural storms that occurred at Avdat (Goossens and Offer, 1990; Offer and Goossens, 1994). The tests showed a good agreement between the wind tunnel patterns and the field patterns (89 per cent agreement for the deposition maps, 80 per cent agreement for the erosion maps), indicating that the wind tunnel patterns are a good replica of the true field patterns.

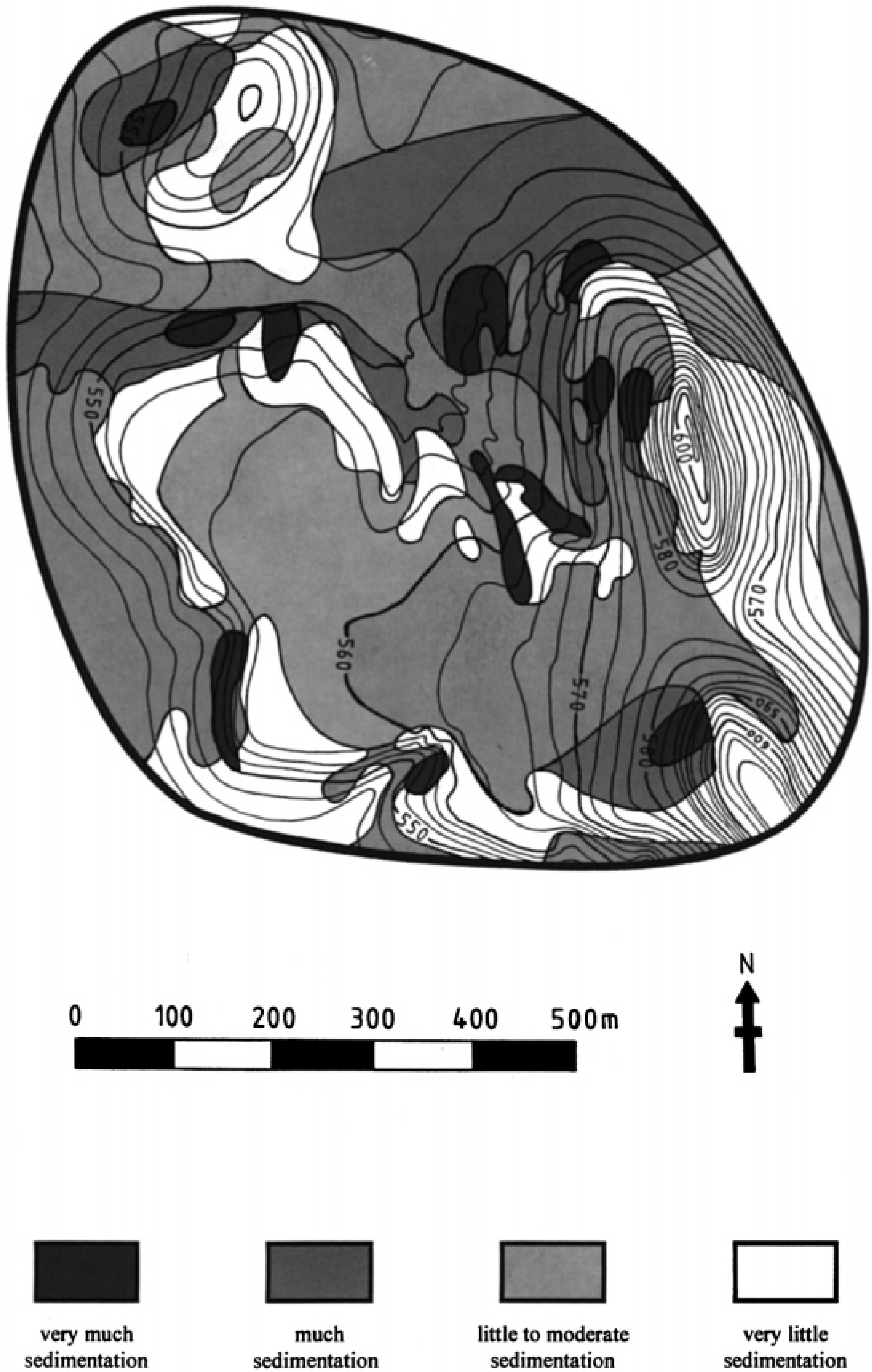

Figure 3. Dust deposition pattern on the topographic scale model (NW wind simulation)

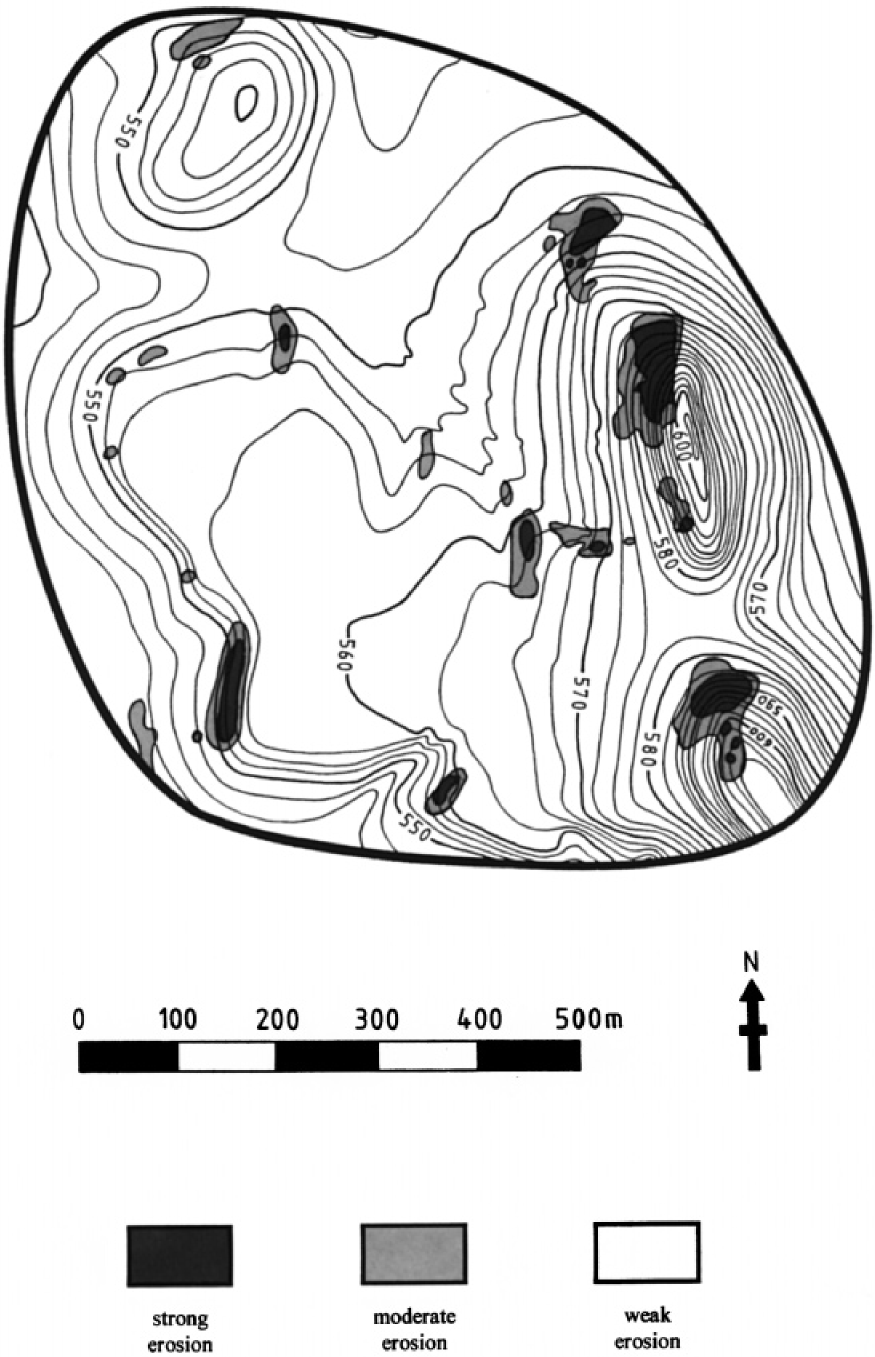

Figure 4. Dust erosion pattern on the topographic scale model (NW wind simulation)

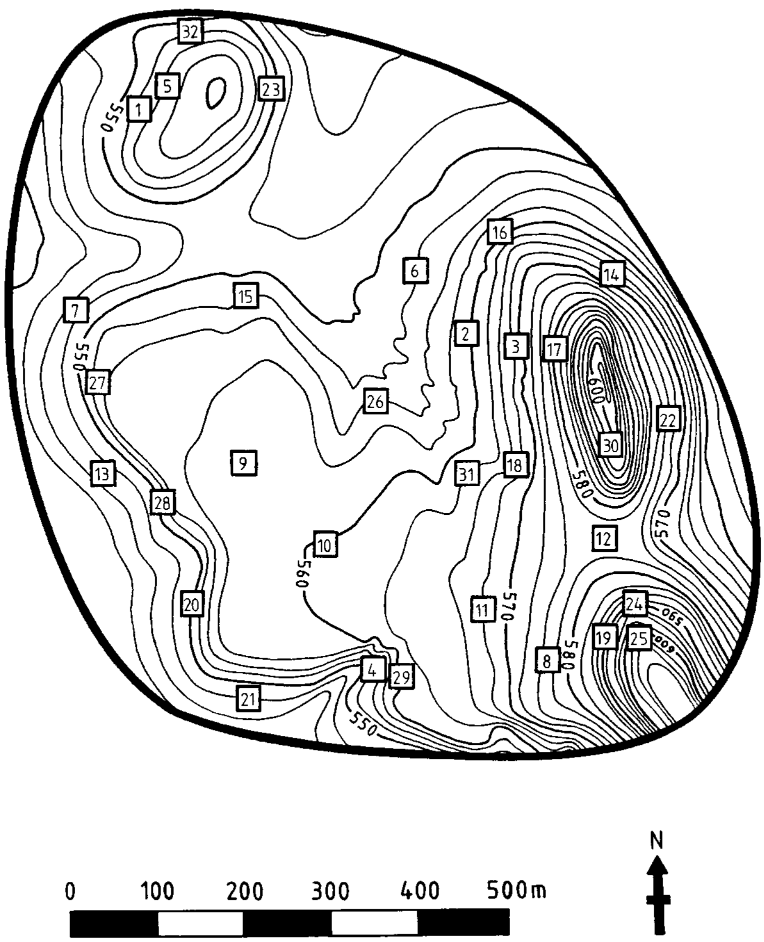

Figure 5. Location of the 32 plots originally installed

The accumulation classes

To predict the (dry) aeolian accumulation near Avdat, I combined the wind tunnel deposition and erosion maps obtained earlier. Since, in this part of the Negev, the winds blow predominantly from the NW, I used the maps obtained during the NW wind simulations to determine the location of the accumulation plots that would be installed in the field. As will be shown in the next section, the wind blew predominantly from the NW quadrant during nearly the whole of the field experiment, so the option chosen was correct. Figures 3 and 4 show the wind tunnel maps.

Combining the information in Figure 3 and 4, the following accumulation classes were selected.

- *Very much accumulation*: this occurs when there is a very high rate of deposition and no (or almost no) erosion. Areas that meet these conditions are rare, since the places of highest dust deposition (windward slopes near their transition from concave into convex) are usually also very sensitive to wind erosion. Only four locations could be selected in the test field (plots 1–4, see Figure 5).
- *Much accumulation*: this occurs when there is high deposition and not-too-strong erosion, or when there is moderate deposition but no erosion. Places that meet the first condition are mainly found on gentle (not-too-steep) windward slopes: plots 5–8. Places that meet the second condition occur on the 560 m plateau (plots 9–12) and on slopes parallel to the wind (plots 13 and 14).

Table I. Morphometric characteristics of the pebble surfaces on the accumulation plots

Plot no.	Experimental area (cm^2)	Number of pebbles	Cover density (%)	*b* (cm)	CSF	*a/b*
1	400	39	40·0	1·96	0·37	1·34
2	400	40	40·0	1·94	0·38	1·33
3	400	41	40·1	1·93	0·36	1·33
4	400	40	39·8	1·94	0·36	1·34
5	400	40	40·0	1·94	0·35	1·35
6	400	40	40·0	1·94	0·37	1·34
7	400	40	40·0	1·93	0·37	1·36
8	400	40	40·0	1·93	0·37	1·36
9	400	41	39·8	1·90	0·35	1·35
10	400	40	40·0	1·96	0·35	1·33
11	400	41	39·9	1·94	0·34	1·31
12	400	41	40·0	1·91	0·36	1·32
13	400	40	40·0	1·93	0·37	1·37
14	400	40	40·0	1·93	0·37	1·35
15	400	40	40·1	1·95	0·37	1·34
16	400	41	40·0	1·91	0·35	1·35
17	400	40	40·0	1·95	0·35	1·33
18	400	40	39·9	1·93	0·36	1·35
19	400	40	40·0	1·94	0·35	1·34
20	400	41	40·0	1·91	0·35	1·35
21	400	40	40·0	1·95	0·35	1·34
22	400	41	40·1	1·91	0·37	1·35
23	400	41	40·0	1·94	0·35	1·32
24	400	41	40·1	1·92	0·35	1·34
25	400	41	40·2	1·92	0·35	1·35
26	400	41	39·9	1·92	0·36	1·34
27	400	41	39·8	1·91	0·36	1·35
28	400	41	40·0	1·87	0·36	1·35
29	400	41	40·0	1·91	0·35	1·35
30	400	41	39·9	1·93	0·35	1·33
31	400	41	40·1	1·93	0·36	1·33
32	400	40	40·1	1·95	0·36	1·35

a = largest pebble diameter; b = intermediate pebble diameter; c = shortest pebble diameter; CSF = Corey shape factor (CSF = $c/(ab)^{0.5}$)

- *Little accumulation*: this occurs when there is much deposition but also much erosion, or when there is little deposition but also little erosion. For the first case, several examples exist at areas where steep windward slopes change from concave into convex: plots 15–20. For the second case there are sites on sufficiently steep leeslopes: plots 21–23.
- *Very little accumulation*: this occurs when there is little (or very little) deposition and strong erosion. It is especially the convex windward slopes that meet this criterion. There are many examples in the Avdat field: plots 24–32.

Altogether, 32 accumulation plots were thus selected.

THE FIELD EXPERIMENT

The accumulation plots

Near Avdat, the surface is covered by pebbles resting on bedrock. To simulate this situation, the accumulation plots consisted of a metal plate (simulating the bedrock) covered by a predetermined quantity of pebbles. The pebbles were collected from a quarry in Kessel-Lo, Belgium, and were similar in size to the Avdat pebbles. They were carefully selected with respect to their size, shape and roundness. From all the

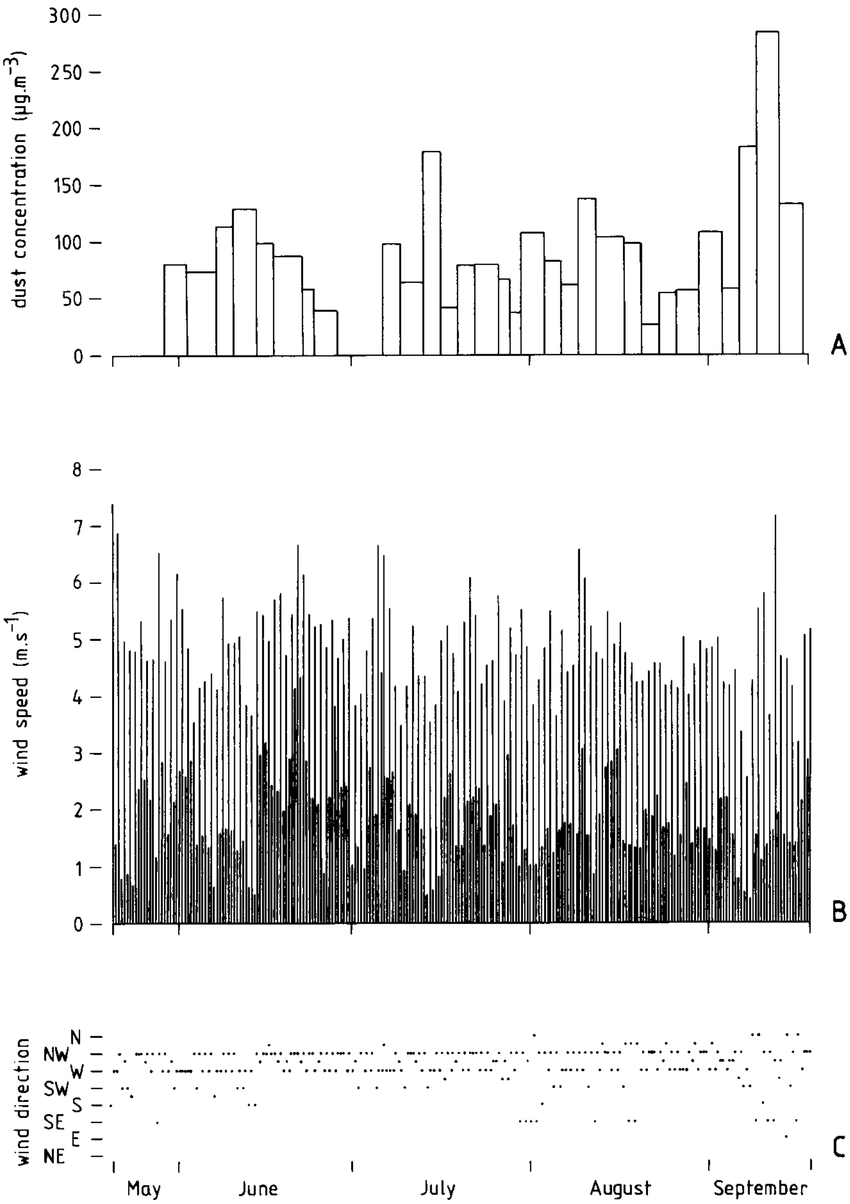

Figure 6. Meteorology of the experimental period: (A) dust concentration; (B) wind speed; (C) wind direction. For the wind, data represent average values for periods of 12 hours

pebbles selected, the longest axis (a), the intermediate axis (b) and the shortest axis (c) were measured, and flattening and eccentricity were calculated. Flattening was quantified by means of the Corey shape factor (CSF), defined as $c/(ab)^{0.5}$ (Corey, 1949), and eccentricity by the ration a/b. Only perfectly rounded pebbles were used.

Sufficient pebbles were selected to construct 32 accumulation plots with identical characteristics. Table I shows the characteristics of each plot. The test section of each plot consisted of a 20 cm × 20 cm square, located in the centre of the 40 cm × 40 cm metal plates. This test square was homogeneously covered by the

pebbles. In deserts, the orientation of rock fragments is usually random, at least outside the talweg of the wadis (Goossens, 1995). It was not possible to install the pebbles on the test plots in random orientation, as this would require very large plots. To approximate a natural distribution, pebbles were put on the plots with their longest axis alternately parallel and perpendicular to the local slope orientation. To avoid any disturbance in this position during the experiment, pebbles were glued to the metal plates using only a single droplet of glues (just enough to fix them to the plates). The plates were installed at the locations selected earlier (see Figure 5), at an angle equal to the local slope angle. After installation, the pebble-free areas on the plates (surrounding the 20 cm $\times$ 20 cm test squares) were covered by local pebbles having the same size as the test pebbles. All local pebbles were carefully cleaned with water to remove all dust. When installed on the plates, they were completely dry, as were the test pebbles.

Installation of the accumulation plots was carried out with great care to avoid any artificial effects on the accumulation. The plots were installed on 20 and 21 May 1998 and remained outside until 18 September 1998. Dust accumulation was thus measured for a period of 120 (or 121) days, or 4 months, during the dry season. This allowed us to investigate the dry aeolian accumulation rate, avoiding any disturbance by water flow.

After the experiment, the pebbles were carefully washed with demineralized water and the quantity of dust that had accumulated on the pebbles alone was determined by weighing the sediment after the water had been evaporated in an oven. The dust that had accumulated underneath and between the pebbles was collected with a (hard) brush and was weighed on the same scale.

Meteorology of the experimental period

Wind speed, wind direction and airborne dust concentration during the experiment are shown in Figure 6. Wind was measured at a height of 3·5 m at the Avdat meteorological station, which is located some 50 m southeast of accumulation plot no. 1 (see Figure 5). Airborne dust concentration (at a height of 1 m) was measured at the meteorological station at Sede Boqer, some 7 km north of Avdat. Wind speed and direction were measured on a continuous basis (on a chart drum) and the values shown in Figure 6 represent the average for the day (08·00–20·00) and the night (20·00–08·00), respectively. Airborne dust concentration was measured for periods varying from 48 to 120 h (2 to 5 days) with a Sierra ultrahigh volume sampler and the values shown in Figure 6 represent the average for each period.

Average wind speed during the experiment was 4·82 m s^{-1} (during the day) and 1·84 m s^{-1} (at night). Average speed for the total period was 3·33 m s^{-1}. Highest winds occurred on 20 May and 12 September, when the 12 hour average exceeded 7 m s^{-1}. Lowest wind was recorded on 8 September, with a 12 hour average of only 0·4 m s^{-1}.

Wind direction was between N and W during nearly the whole experiment. NW winds account for 38 per cent, WNW winds for 10 per cent and W winds for 29 per cent of all winds. Highest winds (>7 m s^{-1}) occurred during W and WNW winds. Average wind direction during the experiment was thus not entirely NW, but WNW.

Dust concentration was highest in September. The most dusty periods were 13–16 July (178 μg m^{-3}), 6–9 September (183 μg m^{-3}) and 9–13 September (284 μg m^{-3}). Average concentration for the total experimental period was 93 μg m^{-3}. No heavy dust storms or dust hazes (concentration >1000 μg m^{-3}) occurred during the experiment.

The accumulation results

When the accumulation plots were taken from the field on 18 September 1998, it appeared that several of them had been destroyed by the local population. From several plots the well rounded test pebbles in the central square had been removed (the more irregular local pebbles appeared to be much less attractive), and other plots had simply disappeared. It was mainly near the isolated hill in the east of the test field that the plots had been destroyed; elsewhere in the region there were fewer problems. Altogether, nine plots were lost during the accumulation experiment. Data are thus available for 23 plots only. In Figure 7, which shows the accumulation results, the destroyed plots are no longer indicated (their position can be found in Figure 5).

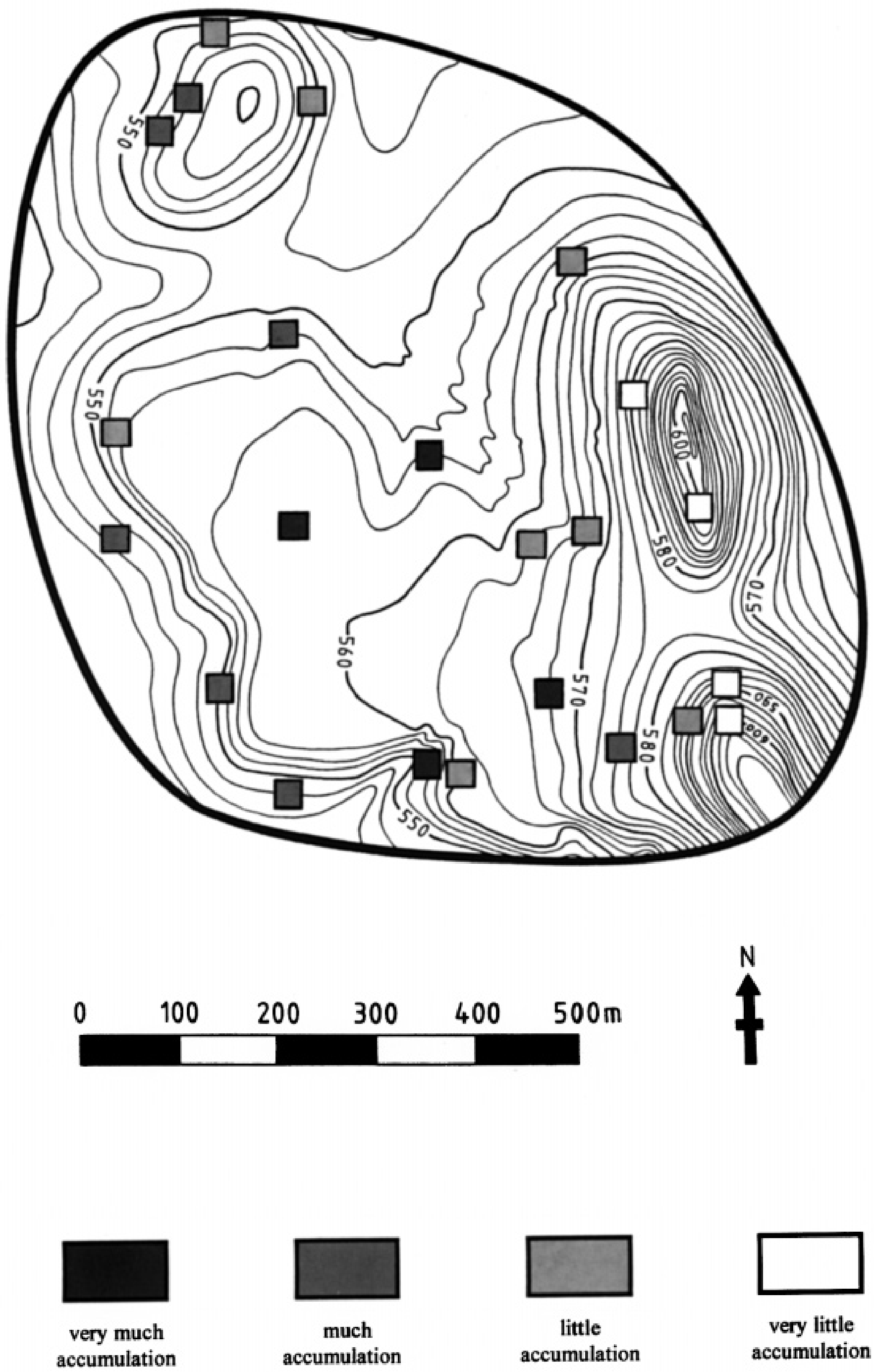

Figure 7. Dry aeolian dust accumulation measured in the field. Only the plots for which data are available are shown (position of the other plots can be found in Figure 5)

Table II. Comparison of the predicted and the measured accumulation for the 23 plots for which accumulation data are available.

Plot no.	Dust accumulation (g m^2)	Predicted accumulation class*	Measured accumulation class*	Assessment†
1	15·84	++	+	+
2	21·23	++	++	++
5	15·64	+	+	++
8	17·95	+	+	++
9	31·07	+	++	+
11	21·28	+	++	+
13	16·28	+	+	++
15	18·33	−	+	−
16	12·69	−	−	++
17	8·50	−	−−	+
18	10·79	−	−	++
19	14·12	−	−	++
20	17·15	−	+	−
21	17·90	−	+	−
23	10·86	−	−	++
24	5·79	−−	−−	++
25	7·50	−−	−−	++
26	24·64	−−	++	−
27	14·08	−−	−	+
29	12·90	−−	−	+
30	9·94	−−	−−	++
31	12·94	−−	−	+
32	13·80	−−	−	+

* ++ = very much accumulation; + = much accumulation; − = little accumulation; −− = very little accumulation
† ++ = perfect agreement; + = acceptable agreement; − = disagreement

To compare the field accumulation with the predicted accumulation, four field accumulation classes were selected, similar to the predicted accumulation: 'very much accumulation', 'much accumulation', 'little accumulation' and 'very little accumulation'. Apart from plot no. 9 (31 g m^{-2}), the accumulation on the plots was always between 5 and 25 g m^{-2}. Dividing this interval into equal subintervals, the following class boundaries were adopted: 5–10 g m^{-2} (very little accumulation), 10–15 g m^{-2} (little accumulation), 15–20 g m^{-2} (much accumulation) and >20 g m^{-2} (very much accumulation).

Results are shown in a qualitative way in Figure 7 and in a quantitative way in Table II. The map in Figure 7 will be discussed later in the paper; first, it is necessary to compare the predicted with the measured accumulation.

The assessment of the wind tunnel predictions was made as follows. Optimum agreement (++ in the last column of Table II) is reached when the predicted accumulation class coincides perfectly with the measured accumulation class. Acceptable agreement (+ in the last column of Table II) occurs when 'very much accumulation' was measured at places where 'much accumulation' was predicted (or *vice versa*), and when 'very little accumulation' was measured where the prediction suggested 'little accumulation' (or *vice versa*). At these places, the wind tunnel technique is still able to tell us whether we may expect much or not much accumulation. Disagreement (−in the last column of Table II) occurs when the wind tunnel predictions are clearly wrong, predicting much accumulation (++ or +) where only little accumulation (− or −−) was observed in the field (or *vice versa*).

Table II shows that of the 23 plots for which data are available, 11 plots (48 per cent) show a perfect agreement between the predicted and the measured accumulation. Eight plots (35 per cent) show an acceptable agreement, and in four plots (17 per cent) the results disagree. Thus, for 19 plots (83 per cent), the accumulation is at least acceptably predicted by the wind tunnel technique.

DISCUSSION

The experiment shows that the medium-term (a few months) dry aeolian accumulation of dust in a rocky desert can be predicted fairly well by short-term (a few minutes) deposition and erosion simulations in a wind tunnel. Although the final accumulation in the desert also depends on later redistribution of the sediment by water, this conclusion is important since only a part of the sediment will be evacuated from (or redistributed over) the catchment. Much of the sediment, especially the grains that are well protected by the pebbles, is not transported, and these grains will contribute to the development of a dusty horizon in the first few decimetres beneath the desert surface. Infiltrating water may help small particles to penetrate the pores and the cracks of the desert floor, thus reinforcing the process. Also, biological activity brings the dust deeper. At Avdat, the dust-rich subzone underneath the surface locally reaches depths of 50 cm and more, as can be observed in a few excavations near the western border of the 560 m plateau. Of course, at locations where the accumulation of dust is small (such as on the steep convex slopes of the hills in the east of the test field), the dusty subzone is much thinner, although it remains visible at many of these locations.

From Figure 7, it is possible to predict the dry accumulation pattern of aeolian dust in a rocky desert.

- Highest accumulation occurs primarily on windward slopes, especially on their lowest part (i.e. the concave zones). Slopes parallel to the wind also accumulate much dust, but usually less than steep concave windward slopes.
- Little accumulation occurs on the upper part of windward slopes, i.e. the convex zones, especially where the degree of curvature is high (but not extremely high). Accumulation is also small in areas located immediately downwind of zones of convex curvature (i.e. in the dust separation bubbles).
- Very little accumulation occurs where the degree of curvature of convex windward slopes is very high (e.g. immediately upwind of the top of isolated or sharply expressed hills), and also on the leeslopes.

In general, the dry aeolian accumulation of dust is (much) more pronounced on the windward slopes than on the leeslopes, except for a zone immediately upwind of the top (including the top itself) of well pronounced hills, where accumulation is very small due to the high degree of convex curvature.

Although the accumulation in the field is fairly well predicted by the wind tunnel, it is important to investigate the cases where the technique fails. Table II shows that there are four plots where the wind tunnel results and the field results disagree: nos 15, 20, 21 and 26. Plot no. 21 is not really a problem, since it is located on a slope showing a slight WNW–ESE orientation. As explained earlier, average wind direction during the field experiment was merely WNW instead of NW. This means that plot no. 21 is located on a slope more or less parallel to the wind instead of on a leeslope, as originally planned. As mentioned earlier, the predicted accumulation on slopes parallel to the wind is high but not extremely high (accumulation class +), and this agrees with the accumulation measured in the field. Thus, taking into account the real wind direction during the field experiment, the accumulation at plot no. 21 is correctly predicted by the wind tunnel. For the other three plots (nos 15, 20 and 26), however, the predictions are definitely wrong.

The major areas where the wind tunnel technique fails are the moderately steep convex windward slopes (steep convex windward slopes behave well), and the zones where the curvature of windward slopes changes from concave into convex. For the five plots that correspond to the first case (nos 26, 27, 29, 31 and 32), no plot is correctly predicted (four acceptable predictions, one wrong prediction). For the six plots that correspond to the second case (nos 15, 16, 17, 18, 19 and 20) there are three good predictions and one acceptable prediction, but also two wrong predictions. Thus, it is mainly near the inflection lines on the windward slopes that predictions are poor. In general, the measured accumulation at these locations is larger than the predicted accumulation. It should be emphasized, however, that locating the exact position of an inflection line in the field is a very difficult task due to the natural irregularities that occur in every field slope. This was explicitly verified for the plots nos. 26 and 32, where it was extremely difficult to decide where exactly the plot had to be installed in the field. Therefore, it is reasonable to state that for many plots, the difference between the predicted and observed accumulation is not due to a conceptual failure of the

prediction technique used but results from local topographic irregularities too small to be included in a 1:2500 scale model.

Finally, the rate of dust accumulation measured during the field experiment can be compared with medium- to long-term accumulation rates published in the literature. For the Negev, data are available from a study by Gerson and Amit (1987). These authors calculated the rate of long-term dust accumulation from measurements of the dust content in coarse desert alluvium. They arrived at rates varying from 0·02 to 0·05 mm $year^{-1}$, or, for a dry bulk density of 1·5 g cm^{-3}, from 30 to 75 g m^{-2} $year^{-1}$. The accumulation measured during our field experiment is of the order of 10–20 g m^{-2} for most plots (see Table II), corresponding to an accumulation rate of 30–60 g m^{-2} $year^{-1}$. This is almost exactly the rate calculated by Gerson and Amit (1987). Several points should be borne in mind, however. First, our rate slightly underestimates the real accumulation since no heavy dust events occurred during the experimental period. Events with high dust concentrations, either dust storms or dust hazes, are very important with respect to the accumulation of dust on the surface. The occurrence of even a single event may markedly increase the average accumulation recorded over a much longer period, for example a complete month (several examples can be found in studies by Goossens and Offer (1995) and Goossens (1996b)). On the other hand, our rate refers to *dry* accumulation only, whereas the rate calculated by Gerson and Amit refers to total accumulation (i.e. the effects of water during the wet season are cleared in the accumulation rate). There is little doubt that some of the dust accumulated during the dry season will be evacuated during the wet season, especially during heavy rains or floods. However, the total amounts of dust eroded by water are rather small in the Negev. Studies by Yair and Klein (1973), Yair and Lavee (1981), Evenari *et al.* (1982) and Schick and Lekach (1993) show erosion (by water) of between 7 and about 20 g m^{-2} $year^{-1}$ for the Negev, i.e. much smaller than the dry accumulation rate. This explains the existence of the dusty horizon immediately underneath the desert surface in this part of the world.

Taking into account both effects, the accumulation rate measured during the field experiment fits very well to the medium- to long-term dust accumulation rate calculated by Gerson and Amit (1987). However, our experiment shows that the accumulation is strongly influenced by the local topography.

CONCLUSIONS

The spatial pattern of the medium-term dry aeolian dust accumulation in a rocky desert can be adequately predicted with the help of short-term deposition and erosion experiments in a wind tunnel. The superposition of the deposition and erosion maps produced during such experiments leads to acceptable predictions of the medium-term accumulation pattern. In the field experiment described in this study, medium-term accumulation was at least acceptably predicted in 19 of the 23 accumulation plots for which data are available. The predictions are somewhat less confident near the inflection lines on windward slopes, where small-scale irregularities in local topography make it difficult to locate the exact position of the areas of little accumulation. For other topographic configurations the wind tunnel method usually works fairly accurately.

The highest accumulation rates occur on concave windward slopes and, to a lesser extent, on slopes parallel to the wind. Little accumulation occurs on the convex part of windward slopes and in flow separation bubbles. The smallest accumulation rates are observed immediately upwind of the top of sharply expressed hills and on the leeslopes.

The rate of dust accumulation measured in the field experiment was of the order of 30–60 g $m^{-2}year^{-1}$, depending on the topographic position. This fits very well with the rate published by Gerson and Amit (1987), who calculated the accumulation from measurements of the dust content in coarse desert alluvium.

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